Technical Report 1112

Effect of Viewing Conditions on Sickness and Distance Estimation in a Virtual Environment

Jennifer A. Ehrlich
University of Central Florida
Consortium Research Fellows Program

February 2000

United States Army Research Institute for the Behavioral and Social Sciences

U.S. Army Research Institute for the Behavioral and Social Sciences

A Directorate of the U.S. Total Army Personnel Command

EDGAR M. JOHNSON
Director

Technical Review by

Bob G. Witmer
Michael J. Singer

NOTICES

DISTRIBUTION: Primary distribution of this Technical Report has been made by ARI. Please address correspondence concerning distribution of reports to: U.S. Army Research Institute for the Behavioral and Social Sciences, Attn: TAPC-ARI-PO, 5001 Eisenhower Ave., Alexandria, VA 22333-5600.

FINAL DISPOSITION: This Technical Report may be destroyed when it is no longer needed. Please do not return it to the U.S. Army Research Institute for the Behavioral and Social Sciences.

NOTE: The findings in this Technical Report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

REPORT DOCUMENTATION PAGE

1. REPORT DATE (dd-mm-yy) February 2000	2. REPORT TYPE Final	3. DATES COVERED (from. . . to) Sep 98 – May 99
4. TITLE AND SUBTITLE Effect of Viewing Conditions on Simulator Sickness and Distance Estimation		5a. CONTRACT OR GRANT NUMBER 5b. PROGRAM ELEMENT NUMBER 622785
6. AUTHOR(S) Jennifer A. Ehrlich (University of Central Florida)		5c. PROJECT NUMBER A790 5d. TASK NUMBER 202A 5e. WORK UNIT NUMBER H01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Institute for the Behavioral and Social Sciences 5001 Eisenhower Avenue Alexandria, VA 22333-5600		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Institute for the Behavioral and Social Sciences 5001 Eisenhower Avenue Alexandria, VA 22333-5600		10. MONITOR ACRONYM ARI 11. MONITOR REPORT NUMBER Technical Report 1112
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT *(Maximum 200 words)*: Previous research indicates that Helmet Mounted Displays (HMDs) using stereoscopic presentation techniques induce greater Simulator Sickness symptomology than a biocular presentation. However, neither of these presentation methods takes into account the different perspective each eye normally receives as a result of each eye turning to fixate on objects in different depth planes, referred to as vergence movements. The present study examined the effects of a vergence algorithm moderating the stereoscopic display in an HMD in a within subjects comparison to standard stereoscopic and biocular presentations. The experiment used a distance estimation task and the other major variable was incidence of simulator sickness. The experiment task required moving through rooms in a virtual environment and providing distance estimates to different objects. The findings suggest that most participants would recover more easily from simulator sickness symptoms with a vergence viewing condition. However, because this study shows a wide range of individual differences, a vergence adjustment to stereoscopic presentation should not be expected to eliminate the number of participants withdrawing, but only to reduce their number when repeated exposures are involved. Also, the range of individual differences indicates a need for multiple measures of symptomology not only to help identify individuals who are under duress, but to better assess when they have adapted. One candidate measure of duress is dark vergence, based on its objective scaling, its relevance to adaptation, and its correlation with SSQ sub-scale scores.

15. SUBJECT TERMS. Virtual environments, Helmet Mounted Displays, Simulator Sickness, vergence, stereoscopic displays

SECURITY CLASSIFICATION OF			19. LIMITATION OF ABSTRACT	20. NUMBER OF PAGES	21. RESPONSIBLE PERSON
16. REPORT	17. ABSTRACT	18. THIS PAGE			Name and Telephone Number)
Unclassified	Unlimited	Unclassified	Unlimited	55	Stephen L. Goldberg (407) 384-3980 DSN 970-3980

Technical Report 1112

Effect of Viewing Conditions on Sickness and Distance Estimation in a Virtual Environment

Jennifer A. Ehrlich
University of Central Florida
Consortium Research Fellows Program

Simulator Systems Research Unit
Stephen L. Goldberg, Chief

U.S. Army Research Institute for the Behavioral and Social Sciences
5001 Eisenhower Avenue, Alexandria, Virginia 22333-5600

February 2000

Army Project Number
20262785A790

Personnel Performance and Training Technology

Approved for public release; distribution unlimited.

FOREWORD

The U.S. Army has made a substantial commitment to the use of networked simulations for training, readiness, concept development, and test and evaluation. Many current networked simulators are designed to provide realistic training and rehearsal for large combined arms groups of vehicles and major weapon systems. These systems represent dismounted soldier activities, but are not intended to directly train individual dismounted soldiers. Virtual Environment (VE) technology, which includes head-mounted visual displays with tracking devices for limbs and individual weapons, has the potential to provide a more immersive, person-centered simulation and training capability for dismounted soldiers. One research challenge is identifying and quantifying the effects of VE system characteristics and features on learning, skill acquisition, retention, and transfer of U.S. Army tasks.

This report describes one experiment in an ongoing program of research conducted by the Simulator Systems Research Unit of the U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) that addresses the use of VE technology for training dismounted soldiers. This experiment investigated the differential effects of three viewing configurations on simulator sickness and distance estimation in a VE. It was expected that adding a dynamically changing perspective (vergence) would result in less sickness and better distance estimation than the biocular and stereoscopic views. The results were not definitive, although it appears that the more realistic vergence presentation does have some advantages over the other two configurations. This advantage was apparent in the ability of the oculomotor system to recover more fully, and the reduced variability in objective and subjective measures of duress after a recovery period. In all conditions distance estimation was poor but related to the individual set point of fixation depth. The greater the distance of this natural set point, the better the distance estimation made by the participant. The findings from this research can be used to recommend VE characteristics and methods that should be incorporated in VE training or rehearsal systems.

ARI's Simulator Systems Research Unit conducts research with the goal of providing information that will improve the effectiveness of training simulators and simulations. The work described here is a part of ARI Research Task 202a, VERITAS - Virtual Environment Research for Infantry Training and Simulation. The research findings were discussed in the Spring of 1999 with U.S. Army Simulation, Training and Instrumentation Command, our partners in the Virtual Environments for Dismounted Soldier Simulation and Training Science and Technology Objective.

Zita M Simutis

ZITA M. SIMUTIS
Technical Director

ACKNOWLEDGMENTS

The author thanks Dr. Michael Singer for his counsel in designing the experiment and analyzing the data, and Dr. David Abbot for his statistical advice.

This research could not have been conducted without the excellent programming and technical support provided by the Institute for Simulation and Training (IST) at the University of Central Florida. The author especially thanks James Parsons and Kimberly Abel Parsons of IST for their creative efforts in producing the virtual environment models and data collection software used in the experiment as well as Bryan Kline for his programming work and Chris Kachurak for modeling the virtual environment.

EFFECT OF VIEWING CONDITIONS ON SIMULATOR SICKNESS AND DISTANCE ESTIMATION IN A VIRTUAL ENVIRONMENT

EXECUTIVE SUMMARY

Research Requirement:

The U.S. Army is committed to using distributed interactive simulations for mission planning, training, rehearsal, concept development, and testing and evaluation. Current systems are designed to provide training for soldiers fighting from vehicles, but are not designed to provide realistic training for dismounted infantry. Virtual Environment (VE) technology provides a new way to simulate real world activities for individual dismounted soldiers. This technology may allow the U.S. Army to cost-effectively conduct planning, training, and rehearsal activities for both individual and collective dismounted soldier tasks. Basic to these simulations is the common context for individual combatants who need to move, observe, shoot, and communicate. A key element in performing basic soldier tasks in VE is the correct perception of spatial information in the visual display. An ancillary aspect of VE display design is the minimization of visual system duress, and optimization of recovery from any stresses arising in VE-based training. Research on the effects of specific VE system characteristics can establish the benefits and problems of training and rehearsing complex activities and tasks using VE technology.

Procedure:

In this experiment, 18 participants estimated distances to some objects and moved towards others in each of three repeated viewing conditions. The Biocular condition presented the same view to each eye. The Stereoscopic view presented slightly offset views to each eye and as if the user were fixated on optical infinity. The Vergence configuration showed slightly offset views to each eye, but dynamically updated the graphics to reflect the change in perspective based upon changing depth planes when fixating objects in the visual array. Objective measures of dark vergence and dark accommodation and the subjective self-report Simulator Sickness Questionnaire (SSQ) were administered before and after each trial as well as after a 30-minute recovery period following each trial.

Findings:

Although the results were not definitive, it appears that the more realistic Vergence configuration does have some advantages over both the Biocular and the Stereoscopic

views. This advantage was apparent in the ability of the oculomotor system to recover more fully based on dark vergence measures as well as the reduced variability in objective and subjective measures of duress after a recovery period. Ancillary analyses also indicate that contrary to earlier research, the Biocular view resulted in greater symptomology and variability in recovery ability than the Stereoscopic condition. In all conditions distance estimation was poor but was related to an individual's set point of fixation depth. Individuals with a more distant natural set point estimated distances better.

Utilization of Findings:

The U. S. Army will employ VE technology for training, mission planning, rehearsal, and test and evaluation. Understanding the effect of different formats of Helmet-Mounted Display presentation during VE experiences will support the cost-effective specification of VE configurations for different uses. Experimental results indicate that there may be an advantage to using a dynamically updating Vergence configuration as it may reduce simulator sickness symptoms and variability in recovery from VE exposure. Reduction in symptoms will be advantageous in training, particularly when repeated exposures to the VE are involved. However, because some individuals might recover better from a Biocular or Stereoscopic viewing condition, it is suggested that research in HMD presentation configurations continues in relation to repeated exposures with more complex visual stimuli and tasks. The development of a pre-exposure test to predict the optimal viewing configuration for each individual would also be useful.

EFFECT OF VIEWING CONDITIONS ON SIMULATOR SICKNESS AND DISTANCE ESTIMATION IN A VIRTUAL ENVIRONMENT

CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

EFFECT OF VIEWING CONDITIONS ON SIMULATOR SICKNESS AND DISTANCE ESTIMATION IN A VIRTUAL ENVIRONMENT

Virtual environments (VEs) are artificially generated and presented surroundings that an individual can experience either passively or actively and interactively through the use of specialized hardware, software, sensors, and actuators. An unfortunate problem in using VEs is simulator sickness. This phenomenon is akin to motion sickness in symptomology, including visual fatigue, dizziness, vertigo, headaches, nausea, and sweating. However, simulator sickness may occur when there is no actual movement or during partial motion (Kolasinski, 1995).

Simulator sickness presents various problems in the use of VE for training, education, or entertainment. People may experience lingering problems with their vision or balance that make tasks such as driving risky for a period of time after exposure. VE systems that are utilized for training may not be optimally used if users focus on the discomfort they feel rather than the task they are learning. Similarly, they may adopt ways of moving in and interacting with a VE that reduce discomfort, but negatively transfer to the real world task. For instance, users may restrict head movements to alleviate disorientation or nausea, or close their eyes periodically to relieve oculomotor discomfort (Kolasinski, 1995). If the task is a search task, such behaviors will reduce skill acquisition opportunities and may result in developing inappropriate behavior patterns. Simulator sickness also reduces the entertainment value of recreational VE systems. Users may become preoccupied with their felt discomfort and efforts to diminish it rather than being fully engaged in the alternate world being presented (Witmer & Singer, 1998). Consequently, we need to know more about simulator sickness and ways to alleviate it.

Simulator sickness is an aggregate construct composed of a number of individual symptoms. These symptoms are often clustered into several component factors: oculomotor discomfort, disorientation, and nausea (Kennedy, Lane, Berbaum, & Lilienthal, 1993). Often nausea receives the most attention, as it is the more dramatic symptom. A recent study indicates that nausea may be the primary reason why people terminate a VE experience, even if they are experiencing oculomotor discomfort or disorientation symptoms (Ehrlich & Kolasinski, 1998). Research frequently focuses on VE characteristics that seem to be most nauseogenic (Kolasinski, 1995). However, oculomotor stress and disorientation continue to be a problem in VE exposure. The current research examines one set of factors that may affect oculomotor discomfort in VEs: the unnatural demands placed on the accommodation and vergence systems in viewing a VE through a helmet-mounted display (HMD). Although the focus will be on visual issues, other aspects of simulator sickness will also be investigated. For clarity and ease of expression, the term VE in this report will refer to an HMD-based VE.

Review of the Literature

In a VE, basic visual perceptual processes are required to work in unnatural ways. These abnormal processes may cause or contribute to oculomotor discomfort in a VE. Therefore, how an object is fixated and focused in everyday visual perception and under

reduced cue conditions will be reviewed. On the basis of that understanding, the abnormal stressful viewing environment of a VE HMD will be discussed. A more detailed summary of simulator sickness will then be presented as a further backdrop for the current investigation.

Visual Stimuli and Processes

When describing and investigating visual processing, we can focus either on factors in the outside world and the interrelatedness of the elements of the world (extrinsic information), or on the machinations of the lens, eye muscles, and neural pathways (intrinsic information). Owens (1987) believes these types of information are dynamically linked together. To perceive extrinsic, light-based information requires visuomotor movements, and the functioning of efferent-based cues requires some light-based extrinsic information. Neither type of information alone can adequately account for all visual phenomena, but both working together offer more explanatory power. The question then arises about which type of information holds greater relative importance in various circumstances. The current study takes this interactive perspective. It alters the graphics presented to the user in order to examine the effect on the intrinsic systems as well as subjective reports of discomfort.

As will be discussed in detail later, extrinsic information in a VE is degraded compared to normal viewing conditions. According to Owens (1984; 1987), when the perceptual cue environment is poor (e.g., cloudy days, dusk, clear skies) extrinsic data is less available and informative. At such times, efferent-based, intrinsic information becomes more dominant because the stimulus environment simply cannot provide the necessary data. Extrinsic information may still be available and used to some extent, but its importance is diminished while intrinsic data becomes more prominent. However, these intrinsic cues are also no longer functioning at their optimal level because they are now receiving degraded information upon which to act. As Owens explains:

> At the same time, the fidelity of this information decreases because the central processes that control oculomotor adjustments depend on retinal stimulation for feedback. With reduced feedback comes a systematic loss of the precision and range of oculomotor control. One consequence of reduced feedback is the appearance of anomalous response biases and interactions among eye movement systems. (Owens, 1987, p. 218)

Accommodation and vergence are the two mechanisms that produce intrinsic information. Accommodation is the process by which the shape of the lens changes to focus on an object. Vergence is the rotating of the eyes inward or outward to fixate on an object at its depth plane. As alluded to above, in a VE where extrinsic information is degraded, intrinsic processes may become relatively more important to perception. Unfortunately, the operating range of both accommodation and vergence in a VE is already decreased because of the deterioration of the extrinsic information. Consequently, the oculomotor system may respond abnormally, resulting in information and perceptual distortion. Some of these responses are examined in the current investigation.

Although they are controlled by different cortical regions, vergence and accommodation are coupled. When a change in one system occurs, it brings about a change in the other (Robinett & Rolland, 1992). However, because of the degraded stimulus conditions, they are less accurate in their machinations and synergism. In fact, at such times both accommodation and vergence tend toward their natural resting states, which are independent of one another (Owens, 1984; Owens & Leibowitz, 1976). Therefore, in the degraded visual conditions in a VE the normal relationship between accommodation and vergence may be upset, leading to distorted perceptions. The current study investigates the hypothesis that the normal link between these processes is altered in VE.

Depth Perception

It is hard to speak of vergence without also alluding to distance or depth in some way or other. Simply put, the eyes converge based on the distance of the object, in order to fixate the image on the foveal retinal field. Therefore, the functioning of the vergence system affects distance perception. Experimental research has indicated that when the vergence system does not respond normally people tend to make poor distance estimations (Leibowitz & Owens, 1975b). The vergence system does not respond normally under reduced stimulus conditions, such as those caused by low illumination, peripherally presented stimuli, and reduced distance cues (e.g., few objects in the environment, low texture). According to Owens (1987), the extent of the abnormal response is a combination of the degree of the degradation of the incoming stimulus, the distance to the target, and the idiosyncrasies of an individual's vergence response system (see below).

Although intertwined, the notions of depth perception and distance estimation are separate concepts. Depth perception is the experience of extension, that objects are not flat and located on a flat plane. It is the perception of a three-dimensional world in which objects are located in three-dimensional Euclidean space. Distance estimation, on the other hand, is a cognitive evaluation of how far or near an object is with regard to some metric (e.g., feet, or meters). It is one way in which we can evaluate at what depth an object is perceived. It is possible that an individual may have a given perception of the depth of an object, but poorly judges the distance when expressing it via a given metric.

The world and objects in the world are laid out in Euclidean space. However, the question arises about what the geometry of perceptual space is. Is it also Euclidean or is there a systematic distortion in the perception of depth? This question is important, because depth and distance are functions of the geometry of space and space's metric. If the metric of space is different in a VE or in different visual configurations of a VE, the user may adapt to this altered space in the same way they adapt to changes in space when wearing prism glasses (e.g., Gallahue, 1982). After this adaptation in the VE, when returning to the real world, the user may again experience a distortion in space until the individual readapts to the metric of the real world. These changes may influence how disoriented an individual feels as a result of VE exposure.

The visual scene in an HMD is presented on flat screens. One of the cues to distance is the linear perspective of the object. However, with an HMD there is no real object upon

which to focus. As such, we may ask to what does the eye converge? Does it converge to the distance of the screen or the depth of a fixated object in the visual presentation as determined by its linear perspective?

There is evidence indicating the eyes do not converge to the distance implied by the linear perspective presented. Artistic paintings for centuries have been drawn on flat canvases presenting implied distances via linear perspective. Enright (1987a, 1987b) discovered in a series of studies using both simple linear perspective line drawings as well as more elaborate paintings that the eyes do not converge to the distance implied by the linear perspective. Although they move in the appropriate direction indicated by the perspective and approximate this point, they do not converge to the precisely correct point. For example, in one set of tests, when viewing different points of a line drawing of a box, the expected change in vergence based on geometry was 1°. Actual changes in vergence ranged from .033° to 1.45°, with a mean of .597° (Enright, 1987a). In addition, this convergence response toward the distance implied in the perspective appears to be involuntary. It is a reflex response, like disparity-invoked vergence. Therefore, we do not know if the vergence in a VE is proper. Based on the work of Enright (1987a, 1987b), we have reason to believe that although the linear perspective presented appears to present a particular distance, the eyes do not converge precisely to that distance in the absence of an actual object in physical space at that depth.

Visual Stress in VE

The intended VE visual stimuli are processed and transformed through the hardware optics and electronics as well as through the software rendering. Only after these alterations occur does the individual receive the stimuli. Below is a brief overview of some of the challenges HMDs present to the visual system.

The standard current HMD design attaches the screen housing to the HMD's helmet or band. The screens are not movable, remaining a fixed distance and perpendicular to the user at all times. Some designers (Fischer, Reiley, Pope, & Peli, in press) are currently developing HMDs that would allow the screens to move and turn in the housing as different depths are fixated. In this way more natural images can be presented and oculomotor discomfort may be reduced.

The luminance level in the HMD is relatively low (Rinalducci, 1996). HMDs use a helmet or band not only as a base upon which to attach the visual screens, but also as a system to block out the real world beyond those screens. Flaps of rubber, foam, or plastic extend out from the screen housing towards the user to keep out light from the surrounding area. This configuration prevents light and stimulation from entering the eyes. As a result, the screen is relatively bright compared to the blacked out surround of the HMD housing.

Because an HMD is an optical instrument, the image is transformed as it passes through the lens system. This process may lead to various types of distortions of the image. For example, the peripheral area may appear flared or the objects minified.

Current HMD hardware does not support the full range of color, hue, and saturation values available in the real world. As a result, it may be hard to distinguish objects from one another if their hues are similar. In addition, the HMD often slips on the user's head. As the screens move away from optimal positioning, the images often become darker, making it difficult to distinguish colors. For example, dark brown and black appear as the same color. Further, the graphics presented on the screens may be very brightly colored or very pure in color, particularly in comparison to the real world. The purer the color the greater the accommodative focusing effort needed (Kandel, Schwartz, & Jessell, 1991) and therefore the accommodative system may be persistently strained while viewing a VE object compared to its real world counterpart.

Normal depth perception does not likely occur in HMD viewing. In fixating an object in different depth planes, the eyes in tandem must turn inward or outward (vergence movements) to align the object in the center of the visual field. However, in an HMD the screens remain fixed in place. Although the eyes may make vergence movements, with the screens being permanently fixed and perpendicular, the viewing angle of the object is distorted. In addition, no real objects are presented for such movements to occur properly. Object depth is mimicked via the computer graphics through linear perspective. However, without real objects being available, vergence movements that do occur based on the linear perspective drawing on the flat screens, may be inappropriate as Enright's (1987a, 1987b) work indicates.

Because the resolution in an HMD is poor, the accommodative system may always be working to try to bring an object into proper focus. Because blur serves as a cue for the focusing (accommodative) system to work to bring the object into focus, the accommodative system may constantly be working to focus the object, because the objects are constantly out of focus. Given that the resolution is so poor, this process is ultimately futile. However, the accommodative system is not under voluntary control, and although the system cannot bring the object into focus, it continues to work to try to bring the object into focus. Further, the accommodative efforts may activate vergence movements. The vergence point may not be the vergence point indicated by the perspective of the graphics or optics of the HMD

Often in rendering a VE scene, the rotation of the eyes is not taken into account in the linear perspective presented to the user. Unless eye tracking is available to determine where the user is looking, the computer calculation of the scene does not include this "rotational" information. As a result, the scene presented to each eye is calculated and drawn assuming each eye is looking directly straight forward, fixating on infinity. However, when fixating an object in the real world, this is not the linear perspective the eyes normally receive. The left eye looks to the right, and the right eye to the left. Thus, the linear perspective for each eye is different and does not have optical infinity as its vanishing point.

We do not know the effect of having or not having such rotational (or vergence) values in VE graphics. The study presented here examines this question. Specifically, it investigates the effect of these vergence calculations on simulator sickness symptoms and distance estimation, as well as other simulator sickness symptoms.

Dark Accommodation and Dark Vergence

According to the dual innervation theory, the resting point of accommodation is a balance point between the sympathetic and parasympathetic muscular forces acting on the lens (Miller, 1990). Parasympathetic activity results in an increase in refractive power. Sympathetic activity, on the other hand, decreases refractive power. As such, dark accommodation (or dark focus) is a tonic state, a balance between parasympathetic and sympathetic activity. When task demands require accommodation be pulled in either direction from this resting state, the accommodative muscles fatigue and the accommodation point changes. Such fatigue occurs only when a task includes viewing distances that are too near or too far from the "normal" or resting state. If no accommodative changes are necessary, no fatigue results (Miller, Pigion, Wesner, & Patterson, 1983; Toates, 1972).

A similar understanding holds for vergence. In other words, there is a natural resting state for vergence. When task demands require vergence effort, vergence muscles are fatigued and the resting vergence point changes.

One way of "locating" the resting state of accommodation and the resting state of vergence is to measure them in the dark. In darkness, there are no cues to accommodation or vergence. Therefore, an individual's eyes revert to their characteristic resting state (Leibowitz & Owens, 1975a; Miller et al, 1983). Consequently, the resting state of accommodation is often referred to as "dark accommodation", and the resting state of vergence is often called "dark vergence". Measuring dark accommodation and dark vergence is a way of measuring ocular demands without measuring actual muscle potentials (Leibowitz & Owens, 1975b). This method of measuring accommodation and vergence fatigue is used in the current study.

As light-based information and cues are reduced, oculomotor movements become biased towards their natural resting state (Owens & Leibowitz, 1976; Leibowitz & Owens, 1975a; Leibowitz & Owens, 1975b). The same phenomenon happens when viewing stimuli through optical instruments with small exit pupils (Leibowitz & Owens, 1975b). In general, under degraded viewing conditions, in which cues to distance are minimal, the eyes tend towards this individual set point. Dark accommodation and dark vergence can measure ocular demands represented by these shifts towards and away from these points.

Distance perception. As mentioned earlier, changes in accommodation and vergence affect distance estimation. A change in perceived distance is not directly determined by the new angle of convergence of the eyes when they fixate an object at a different depth. Rather, it is a function of the deviation of the vergence response from the individual's resting state. The resting state acts as an anchor or calibration point from which deviations are interpreted as a particular depth based upon the oculomotor effort required to fixate the object. Oculomotor effort is important, not as an absolute determinant, but as one relative to the normal resting state of vergence. "According to this view, fixating a target located farther than the dark vergence distance would require divergence effort, which gives rise to increased perceived distance, and fixation of targets nearer than the dark vergence distance

would require convergence effort, which gives rise to decreased perceived distance." (Owens, 1987, p. 239) Therefore, vergence effort needs to be re-conceptualized as effort with respect to the individual's normal set point, and distance perception as a result of this effort. Similarly, Owens and Leibowitz (1976) have found that dark vergence, but not dark accommodation, is significantly related to perceived distance to a light point presented in the dark. Owens and Leibowitz (1980) have found dark vergence ranged from infinity to 50 cm with a mean of 116 cm while dark accommodation ranged from low hyperopia to 28cm with a mean of 76 cm.

Near work. The plasticity of the oculomotor system can become an important factor in task performance as well as oculomotor discomfort. This is particularly true during near work. Not everyone reports visual fatigue when doing near work (Tyrrell & Leibowitz, 1990). The question arises why this is the case. Is it that some people just do not report visual fatigue they may be feeling, or is there an underlying oculomotor or physiological difference between people that causes some individuals to experience discomfort while others do not? As noted above both the resting state of accommodation and the resting state of vergence are plastic. They can shift over time if the task requires it. Thus, there may be an interaction of work distance and the resting state, which determines visual fatigue. The more discrepant the task distance from the resting state, the more oculomotor effort is required to fixate on and complete the task (Tyrrell & Leibowitz, 1990). Similarly, the greater the discrepancy between one's natural set point and the task distance, the greater the shift will need to be (Heuer & Owens, 1989).

Studies have indicated that near work detrimentally affects the visual system (Ostberg 1980; Lie & Watten, 1991; Watten, Lie, & Birketvedt, 1994; Tyrrell & Leibowitz, 1990). For example, Watten, Lie, and Birketvedt (1994) and Lie and Watten (1991) have found that near work fatigues the muscles of the oculomotor system. However, vergence is more fatigable than accommodation. Further, the effects of stressing the accommodative system results in different problems for the individual than stressing the vergence system. Variations in dark vergence, not dark accommodation have been related to subjective reports of visual fatigue during near work (Best, Littleton, Gramopadhye, & Tyrrell, 1996; Owens & Wolf-Kelley, 1987). The magnitude of the shift in the resting state of vergence is positively correlated with reports of visual discomfort. On the other hand, although shifts in the resting point of accommodation have not been correlated with reports of visual discomfort, they have been positively correlated with visual acuity decrements (see Owens & Leibowitz, 1976). For example, Owens and Wolf-Kelley (1987) asked people to read for one hour at a distance of 20 cm. They found an inward shift in both dark vergence and dark accommodation. The shift in dark vergence and dark accommodation were significantly correlated with visual fatigue. On the other hand, a visual acuity loss in one third of their subjects was significantly correlated with the degree of the shifts in dark accommodation, but not dark vergence.

In an interesting study investigating the effects of near visual work, Jachinski-Kruza (1991) examined the relationship between vergence and size (measured as visual angle) on eyestrain. He found that visual strain was greater at a distance of 50 cm than at 100 cm even when the size of the stimulus was twice as large. The visual strain at 50 cm correlated

significantly with the individual's dark vergence. Therefore, although the visual angle was the same, the important factor in determining eyestrain was the vergence effort required by the distance of the task. No correlation between dark vergence and eyestrain was found at 100 cm. Therefore, it is the actual distance of the object to be focused on that is most important, not the size or distance implied by the size of the object.

Interacting with the environment appears to be an important factor in the amount of vergence shift. Owens (1987) conducted a study in which people wore prisms while walking through a building engaging in several psychomotor tasks (e.g., table tennis), rode through the same building without any interaction, or read an illuminated magazine at a fixed distance in an otherwise dark room. Although there was no shift in dark accommodation, dark vergence shifted significantly more for the walkers and riders who actually fixated at varying distances.

Although the visual scene in a VE may present images as if they were some distance away, the screens are actually only a few centimeters away. It is not clear which point the individual converges to: that of the screen, the implied distance in the perspective presented, or some compromise point. Patterson and Martin (1992) suggest it is the screen, while the work of Enright (1987a, 1987b) indicates it may be a compromise point. The present study may shed some light on this issue.

Simulator Sickness

Kennedy, Lane, Berbaum, and Lilienthal (1993) identified three separate subscales of symptoms associated with simulator sickness through their self-report Simulator Sickness Questionnaire (SSQ). The Nausea scale is composed of general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, and burping. The Oculomotor Discomfort scale reflects problems with general discomfort, fatigue, headaches, eyestrain, difficulty focusing, difficulty concentrating, and blurred vision. Finally, a Disorientation scale addresses difficulty focusing, nausea, fullness of head, blurred vision, dizziness with eyes open, dizziness with eyes closed, and vertigo. Stanney and Kennedy (1997) have found that in VE, Disorientation symptoms are greater than Nausea symptoms, which in turn are greater than Oculomotor Discomfort symptoms.

The most prevalent theory of simulator sickness is the sensory conflict theory (Kolasinski, 1995). It is a theory borrowed from motion sickness research (Reason & Brand, 1975), which suggests that sickness is the result of having to resolve contradictory information perceived by the visual and vestibular systems. In a VE, for example, the operator may be seated and using a joystick, trackball, or mouse to navigate through the VE. The visual system is registering self-movement based upon the graphical rendering of the objects in the environment. However, the vestibular system does not detect any actual movement, beyond perhaps the user's fidgeting in the chair. To the extent that the perceptual systems cannot adequately deal with this conflicting information, simulator sickness results. The illusory self-motion produced at such times, known as vection, appears to be an essential factor in producing simulator sickness (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990). However, it may also be appropriate to speak about sensory

conflict within a sense. For example, the split between accommodation and vergence or conflicts in stereoscopic processing may be forms of sensory conflict that the individual is unable to resolve resulting in sickness.

In VE there are two sources of visual information: that produced by the hardware-software environment and the individual's visual system. In an HMD, because two screens are available, one in front of each eye, it is possible to present two different views to the eyes, thus mimicking binocular disparity. If two different views are presented to the user, the individual's perceptual system must merge those views, which results in 3-D stereoscopic images. On the other hand, the same view can be presented to each eye, with no interpupilary distance (IPD) being used (or an IPD value of zero). Such configurations are known as biocular displays.

Mon-Williams, Rushton, and Wann have investigated eyestrain in HMDs (Rushton, Mon-Williams, & Wann, 1994; Mon-Williams, Wann, & Rushton, 1993; Mon-Williams, Wann, & Rushton, 1995). In a study using early generation HMDs, they found participants experienced a number of visual discomfort and nausea symptoms after only 10 minutes of immersion during which they "bicycled" around a VE on a stationary bicycle (Mon-Williams, Wann, & Rushton, 1993). Twenty percent of their participants had a reduction in binocular vision by one Snellen chart line. Three of those participants experienced blurred vision following immersion. However, the symptoms dissipated within 5 minutes. They also found evidence of high stress being placed upon the accommodation and vergence systems. Further, 12 of their 20 participants reported symptoms of simulator sickness such as headaches, sore eyes, nausea, and blurred vision. Only the headache symptoms remained after 5 minutes.

In a study using a later generation HMD, they found much less dramatic problems (Rushton, Mon-Williams, & Wann, 1994). In exposure times lasting up to 30 minutes, few symptoms were reported among their participants, and objective measures did not indicate such strain upon the oculomotor system. The authors suggest these differences may be because the HMD in the second study was a biocular display. They reason that in such a configuration because the two eyes are presented with exactly the same stimuli with no offset to mimic binocular disparity, no conflicting accommodation and vergence cues exist. Their argument appears to be that if there is no disparity from the images to be merged, the eyes need not converge, and no vergence effort is required. Any object moving in and out of depth will be deemed to move in and out of depth only due to 2D pictorial cues, such as occlusion and linear perspective, and not stereoscopic cues such as vergence.

However, biocular configurations may not eliminate conflicts between vergence and accommodation. The user accommodates and converges to points determined by the optics of the HMD. If the VE really is a reduced-cue environment for the visual system, then in keeping with Owens (1984), the eyes may tend towards their resting states of accommodation and vergence. These points, in turn may be independent of one another and thus in conflict. Further, the point the optics have set as the accommodation and vergence point may or may not be the resting point of accommodation, and it may or may not be the resting point of vergence. Therefore, there still can be no guarantee that no conflict exists

for a given individual between accommodation, vergence, and the HMD system. In addition, there have likely been other changes in the optics, resolution, etc., of the later generation HMD. These changes may be more responsible for the differences. Without a direct comparison of stereoscopic and biocular configurations with the same HMD, computer hardware, and computer software, such conclusions remain suspect. The current study undertakes this comparison.

Other researchers conclude that biocular displays also provide inherently abnormal viewing conditions.

> Both monocular and biocular displays deprive viewers of stereoscopic depth information; all three displays use collimated light, which does not allow accommodation to provide differential focus for objects at different distances. These conditions tend to keep the human accommodation and vergence corrective feedback systems in conflict, resulting (with sustained use) in eyestrain, fatigue, and possibly disorientation. (National Research Council, 1997, p.93)

Although Rushton, Mon-Williams, and Wann (1994) found minimal evidence of oculomotor discomfort in a biocular configuration, other research indicates a significant increase in pre- vs. post- exposure eyestrain (as well as disorientation and nausea) even in biocular conditions (see Ehrlich, 1997; Singer, Ehrlich, & Allen, 1998). These problems appear to be particularly apparent the more near-far focal transitions there are (Ehrlich, 1997). The study reported here employs a task requiring numerous near-far focal transitions.

Summary and Hypotheses

One set of symptoms in the aggregate concept of simulator sickness is oculomotor distress. The HMD, which is frequently used in VE, may present an inherently stressful visual environment and pattern of stimuli with which the oculomotor system must work. When

> … an operator fixates a disparate stimulus appearing in a depth plane different from that of the display screen, the stimulus for accommodation (display screen) may be at one distance while vergence angle is appropriate for another distance… thereby producing a mismatch between accommodation and vergence. Such situations are known to produce much discomfort for the operator. (Patterson & Martin, 1992, p. 675.)

This situation is the case in HMDs. In an HMD the processes of accommodation and vergence are constrained by the hardware and software systems. These normally linked processes must be decoupled (Robinett & Rolland 1992). Measuring stress on the accommodative and vergence systems can be done by measuring their "resting point", or the point to which they gravitate in the absence of stimulation, such as in the dark. Thus, measures of dark accommodation and dark vergence are an indirect measure of oculomotor

stress. Because it is a reduced cue environment, research suggests there may be a shift in dark vergence and perhaps in dark accommodation during VE viewing (Owns, 1987). These changes may be associated with oculomotor discomfort factors (Owens & Wolf-Kelley, 1987; Jachinski-Kruza, 1991).

Typically VE scenes are rendered assuming a vergence of infinity. There is a basic split in the points of accommodation and vergence forced upon the user by the software and hardware configurations. When an object moves closer or further away, there is little graphical sensitivity to this movement. The graphics render the view as if the user were looking towards optical infinity. Normally, the perspective each eye receives is rotated rather than pointing towards optical infinity. As an object moves closer, the angle of each eye becomes more extreme as the eye continues to track inward to fixate the object. The opposite holds as an object moves away from the observer. It is not clear what impact the lack of rotational information in VE may have on the oculomotor system and measures of subjective discomfort. Finally, because the distance to which an individual converges is a function of the vergence angle, vergence affects, if not determines, distance perception (Owens, 1987). For example, Owens & Leibowitz (1976) tested the ability to estimate distance between 50cm and 400cm in the dark. They found a correlation of 0.76 between the resting state of vergence and estimated distance. Errors in distance estimation increased as the difference between target distance and dark vergence increased. Further, errors were in the direction of the dark vergence point.

Due to the nature of current VE hardware and software technology, it is possible to present three different types of graphical views to the eyes in a VE. First, the same view can be presented to each eye. This is called a biocular view. Second, the images to each eye can be slightly horizontally offset to mimic the horizontal disparity of the views the eyes normally receive as a result of their physical separation in the head. This is a stereoscopic view. Finally, a view that takes into account the changing perspectives normally perceived as a result of vergence movements when fixating objects at different distances can also be used. When viewing an object not at optical infinity, the right eye points leftward and receives a view based on that perspective, while the left eye points rightward and receives a view based on that perspective. This is referred to as the vergence condition. The present research study investigates the effects each of these three viewing conditions has on dark vergence, dark accommodation, simulator sickness, and distance estimation.

Because a previous study conducted by the author (Ehrlich, 1997) indicated that oculomotor discomfort was greatest in tasks that require more near-far fixation changes, the current investigation required similar activity by the visual system to most effectively test the stresses which may be induced by the different viewing conditions. Based on the literature, it is expected that for those with an initial dark vergence value greater than the vergence point of the HMD, there will be an inward shift in dark vergence as a result of viewing a VE, regardless of condition. If the initial dark vergence value is less than this point, there will be an outward shift. However, after a recovery period, dark vergence will shift back to its initial pre-exposure point. In addition, because it takes into account more facets of normal viewing, the vergence condition will be less stressful than either the biocular condition or the stereoscopic condition as measured by dark vergence, dark

accommodation, and the subjective measure of discomfort (SSQ). There is only partial normal stereoscopic information in the traditional stereoscopic view (disparity but not rotation) so the visual system should have trouble properly matching the stimuli between the eyes, as they will not quite fit the stereoscopic pattern. It is also believed that the same measures will indicate that the biocular condition will be less stressful than the stereoscopic condition based on findings from research comparing biocular and stereoscopic views in HMDs. In other words, the vergence condition should place the least amount of stress on the individual and the stereoscopic view the most stress. There should be significant correlations between the change in dark vergence and SSQ subscale scores as both are indicative of duress. However, there may be no correlation between dark vergence and dark accommodation. Although these processes are normally linked, in a reduced cue environment, they become less systematically linked. Finally, again because the vergence condition better reproduces the normal visual stimuli, distance estimation should be better in the vergence condition than either the biocular or stereoscopic condition. However, because there is some disparity information, distance estimation should be better in the stereoscopic condition than the biocular condition.

In summary, the hypotheses are as follows:

- If the baseline dark vergence value is greater than the vergence point of the HMD, there will be an inward shift in dark vergence regardless of viewing condition.

- If the baseline dark vergence value is smaller than the vergence point of the HMD, there will be an outward shift in dark vergence regardless of viewing condition.

- As dark vergence shifts, there will be a corresponding increase in simulator sickness symptoms as measured by the SSQ.

- Dark accommodation is not expected to shift, because the exposure time is relatively short.

- There will be no correlations between shifts in dark vergence and dark accommodation, because dark accommodation is not expected to shift.

- For all measures except dark accommodation, the vergence condition will be best (least increase in symptoms), followed by the biocular condition, with the stereoscopic condition inducing the greatest discomfort.

- Participants will be able to recover to pre-VE exposure levels on all symptoms for all viewing conditions after a 30-minute rest period.

- Distance estimation will be more accurate in the vergence condition, followed by the stereoscopic condition, while the biocular condition will be least accurate.

Method

Participants

The analyzable data set is comprised of eight males and 10 females ranging in age from 18 years to 32 years with a mean of 21.33 years ($\underline{SD}$ = 4.34). Participants had normal or corrected to normal vision with contact lenses and no history of severe motion sickness after childhood (4 or less on a 7-point scale). One other female terminated the experiment early due to simulator sickness symptoms.

Apparatus

The experiment was conducted at the University of Central Florida's Institute for Simulation and Training's Visual Systems Lab (IST VSL). All software for this experiment was custom-designed and programmed by IST VSL. The visual display graphics were generated using Performer^{tm} and special software developed by the IST VSL. The data capture software was also developed by IST VSL. A Silicon Graphics Reality Engine^{tm} generated the VE. A Polhemous FastTrack^{tm} provided head tracking. Participants viewed the VE through a VR4^{tm} HMD from Virtual Research Corporation. The VR4^{tm} has a 48° H by 36°V field of view, and a vergence point of 1 meter.

Eighteen rooms were designed using MultiGen^{tm}. Rooms were square (33 feet on each side) with plain tan walls and gray floors and ceilings. Two entry/exit doors were situated at the center of opposite walls in the room. The rooms were arranged in three different orders for counterbalancing. Each room had four 1-ft cubed colored blocks (dark blue, light blue, yellow and white) placed at various distances around the room. Two 2 foot tall traffic cones with 1 foot high numbers on their tops were also placed around the room (see Figure 1). Both the cones and blocks were placed so that one item was in each of the following distance ranges from the participant when standing at the entry door to the room: 1-5 ft, 6-10 ft, 11-15 ft, 16-20 ft, 21-25 ft, and 26-30 ft. No objects were directly in front of or behind any others. Alcove walls were placed around the doors to block the view of the next room (see Figure 2). These walls automatically lifted when participants arrived at the door to the next room. Bitmaps of famous paintings were placed on the alcove walls to serve as focal point for participants as they moved towards the wall (see Figure 3).

For the **biocular** condition, the software presented the same view to each eye, as if the "cyclopean eye" was centered between the two eyes (see Figure 4). There was no rotational factor used to mimic the inward and outward rotation of the eyes to view objects at different depth planes. The view was presented as if the user were staring straight ahead at optical infinity.

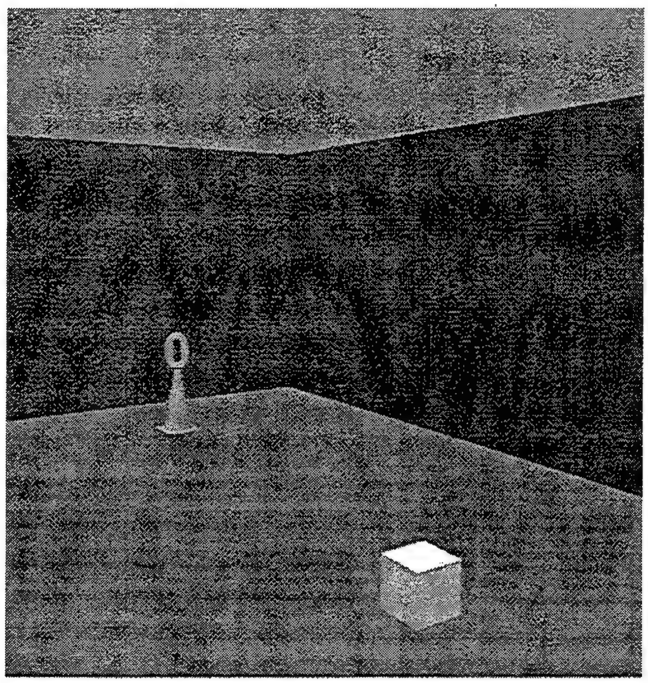

Figure 1. Room with cone and block.

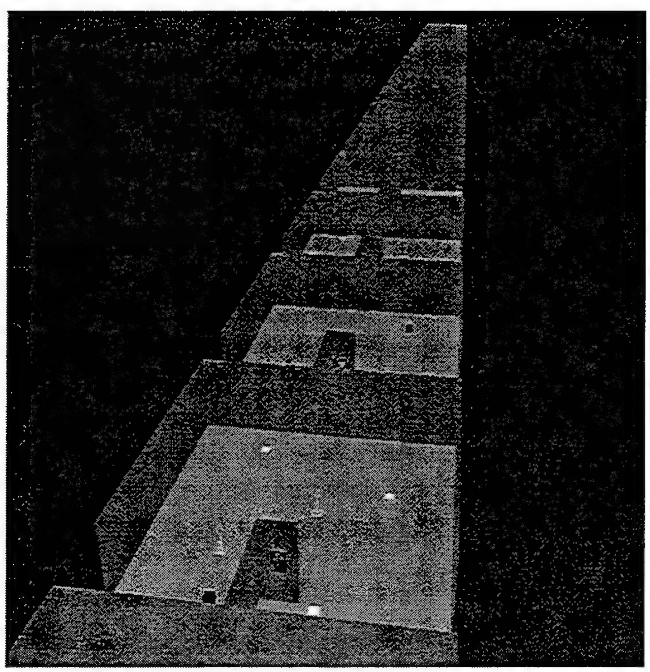

Figure 2. Overhead view of room series with objects and alcoves.

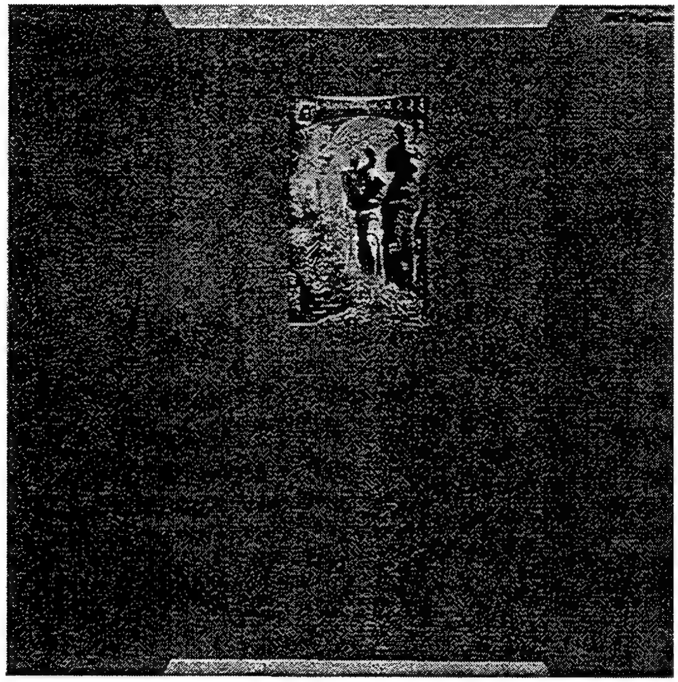

Figure 3. Alcove wall with painting.

In the **stereoscopic** condition (standard VE), slightly different views were presented to each eye (see Figure 4). The software graphically separates the views horizontally from one another to mimic the separation of the eyes in the head, using a standardized interpupilary distance (IPD). However, the user was able to physically adjust the IPD distance for their unique IPD using mechanical adjustments on the Virtual Research Corporation's VR4tm HMD. As with the biocular view, no rotational value was used to calculate the view.

Finally, the **vergence** condition, like the stereoscopic condition, presented slightly horizontally offset views (see Figure 4). However, it also added in a rotational value. This rotational factor angled the vantage point from which each eye's visual presentation based upon how far away a virtual object was from the observer's position in the VE. The right eye received a view determined by its leftward orientation and the left eye a view determined by its rightward orientation. The software determined which object was in the center of the field of view and used basic trigonometric functions to determine the necessary angle of rotation. This presented perspective graphics to each eye representing the view the eye would normally receive in sensing an object at that particular distance.

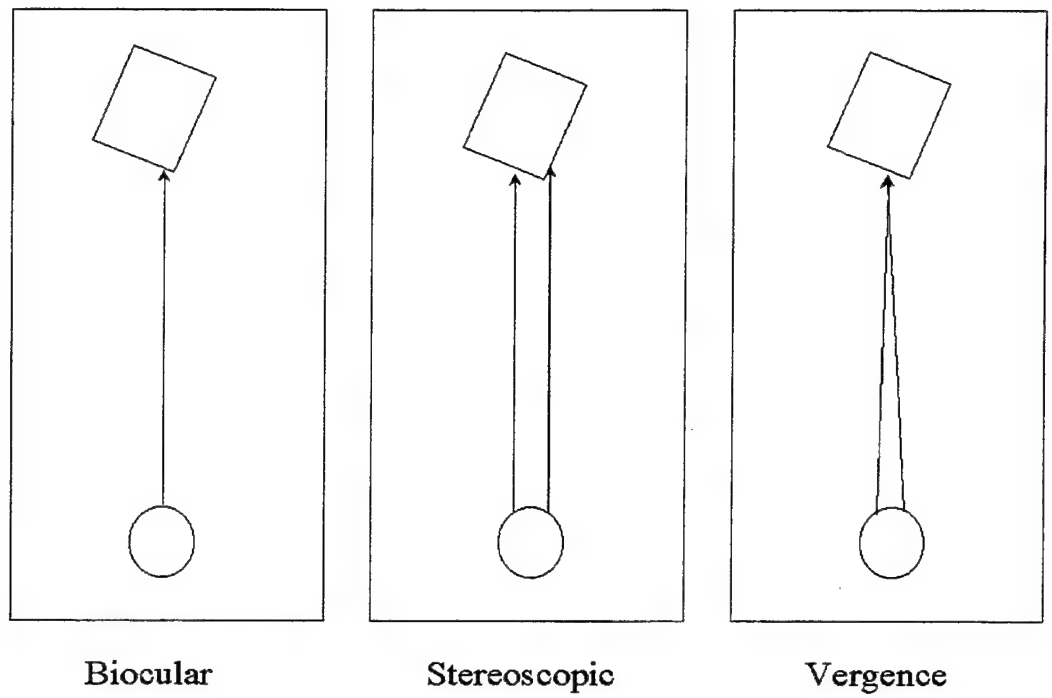

Figure 4. Viewing conditions.

The data collection software recorded the following information every 0.5 seconds: time, head yaw, head pitch, head roll, movement type (none, towards a cone, or moving into the next room). If movement toward a cone was detected, the cone number was also entered at that time.

Procedure

Participants were pre-screened over the telephone before scheduling their experimental session. The pre-screening covered vision requirements (normal or corrected to normal with contact lenses), motion sickness and epilepsy history.

All data collection occurred at IST. When participants arrived for their experimental session, they were given a prebrief describing the purpose and procedures for the study. The experimenter answered any questions they may have had about the study, and they then signed an informed consent form. A biographical data form and a baseline Simulator Sickness Questionnaire (SSQ) were administered and served as a final screening to assure eligibility to participate. After this final screening, participants were randomly assigned to one of the counterbalance orders.

Participants watched a video of the virtual environment and the task. The task itself was straightforward and a previous study using a similar task indicated that people adjust to the task quickly (Kolasinski, 1996), so no special training session appeared necessary. Any formal training session fully immersed in the HMD would have compromised the data for the initial trial run, as the participant would have had to have been immersed in one of the three conditions.

Initial dark vergence and dark accommodation measures were then taken to establish the pre-exposure baselines for each individual. Dark accommodation was measured by a hand held Stigmatoscope. This device is a lightweight, telescoping optical instrument. Participants held the Stigmatoscope up to their self-selected preferred eye and moved the telescoping section inward or outward to focus the internal light source. This procedure was performed four times, twice beginning with the telescoping barrel extended all the way out; and twice beginning with it compressed all the way in. The final dark accommodation measure was the average of these four values.

For the dark vergence measure, participants were tested in a dark room which had a red flashing light affixed to the wall. Participants wore a pair of glasses that had no lens in one eye and a horizontal grating over the other. The eye that had no lens in the glasses saw a flashing light as a small dot. The other eye saw the flashing light as a flashing vertical line. Participants then moved towards the light until the dot and the line appeared on top of one another. The distance from the wall was then measured and used at their dark vergence.

After these preliminaries participants sat down in a swivel chair and the experimenter demonstrated how to use the joystick for this experiment as well as put on and adjust the HMD. Once participants were comfortably situated with the HMD, their view was reset and the experimental trial began. A separate monitor allowed the experimenter to see the visual scene being presented to the participant.

Three experimental trials were completed. In each trial participants received a different viewing condition, experiencing all three conditions over their three trials. The order of the viewing conditions for each trial was counterbalanced over all participants in the study. Participants began a trial facing a picture on an alcove wall over the door into the first room. The experimenter raised the alcove wall, revealing the first room. Participants were reminded that the cubes were 1-ft on each side. The experimenter then designated a particular colored block, which they were to locate, place in the center of their field of view and then estimate the distance to that block. A second block color was then indicated and participants estimated distance to it. Next, the experimenter specified a number corresponding to the number on top of one of the two cones in the room. Participants located that cone and once it was centered in their field of view the experimenter enabled the "move mode" and they began to move toward the cone at a constant rate of 2-ft/sec. Movement only occurred if the cone remained centered in the field of view. As they moved towards the cone, the numbers on top of the cone changed randomly every 2-5 seconds. Participants identified these characters as they changed. Finally, upon arrival at the cone, participants pressed a button on the joystick control and automatically moved into the next room. They were asked to look in the direction of movement with their head as they

approached the next room. As they approached the next room, they entered the alcove with a painting on it. When they arrived at the door to the next room, the alcove walls automatically lifted revealing the next room. The above procedure was repeated for each of the 18 rooms in the series. Each trial lasted 15 minutes. After 15 minutes, the trial ended, regardless of where in the series of rooms participants were.

Immediately following each trial, during a 30-minute intertrial interval the dark vergence, dark accommodation, and post-exposure SSQ tests were administered. Beyond completing the post-exposure tests, no other activities were undertaken (e.g., participants were not allowed to read), so that visual recovery was not influenced by any activities which might have required near focusing.

After the 30-minute intertrial interval, another series of pre-exposure baseline measures of the SSQ, dark accommodation, and dark vergence were taken and the next trial was begun. A total of three trials with a half hour intertrial interval after each trial were completed. Thirty minutes after completing the final trial, the SSQ, dark accommodation, and dark vergence measures were taken. If serious symptoms persisted at this point, participants were retained on site until their symptoms dissipated. However, none of the completing participants required extra time before leaving the experimental site. The one participant that dropped out after one trial stayed for a total of 1 hour and 15 minutes post-exposure before returning to near normal.

Participants were then debriefed and paid or given credit for their time. After the experimenter answered any questions they had about the experiment, they signed a post-experimental release form stating they felt in adequate health to drive and that they would contact the experimenter if they experienced any delayed symptoms. No participants contacted the experimenter.

Results

The study was a two factor repeated measures design with three viewing conditions and three counterbalanced repeated measures for each viewing condition across six dependent variables. The three viewing conditions (VIEW) were Biocular, Stereoscopic, and Vergence. The six dependent measures were dark vergence (in centimeters); dark accommodation (in diopters); and the three SSQ subscale scores of Nausea, Oculomotor Discomfort, and Disorientation, plus the overall Total Severity SSQ. Each of these measures has three administration (ADMIN) values: pre-exposure (PRE), immediate post (POST), and after the 30-minute recovery or intertrial period (RECOVERY) value. In addition, the first pre-exposure baseline value was taken prior to the first trial for each measure (PRE-VE) regardless of the assigned viewing condition.

Dark Vergence

The PRE, POST, and RECOVERY means, standard deviations, and variances for dark vergence by viewing condition are presented in Table 1.

Table 1
Means and Standard Deviations of Dark Vergence by View

Variable	Mean cm (diopters)	Standard Deviation	Variance
Pre VE	225.99 (.4425)	93.48 (.1550)	8738.21 (.0240)
Pre Overall	213.19 (.5438)	96.22 (.1989)	9258.87 (.0396)
Post Overall	170.30 (.7629)	108.78 (.3287)	11833.60 (.108)
Recovery Overall	206.87 (.5745)	98.33 (.2316)	9669.05 (.0534)
Pre Biocular	214.14 (.5523)	100.43 (.2339)	10086.18 (.05471)
Post Biocular	169.19 (.8261)	120.87 (.4191)	14610.70 (.1756)
Recovery Biocular	206.09 (.5956)	97.58 (.2800)	9521.77 (.07837)
Pre Stereoscopic	211.67 (.5711)	105.32 (.2503)	11092.25 (.06263)
Post Stereoscopic	169.55 (.7571)	111.02 (.3193)	12324.54 (.1019)
Recovery Stereoscopic	201.86 (.6042)	105.87 (.2582)	11208.60 (.0666)
Pre Vergence	213.78 (.5464)	90.98 (.2190)	8277.02 (.04796)
Post Vergence	171.45 (.7347)	97.60 (.3072)	9525.03 (.09438)
Recovery Vergence	212.65 (.5543)	98.60 (.2162)	9721.47 (.04673)

Repeated measures ANOVAs on the dark vergence measure revealed a main effect only for ADMIN ($F(2, 34) = 8.73$, $p < .001$) and no effect for VIEW or interaction of VIEW and ADMIN. Because there were more than two groupings involved in this analysis it was important that the sphericity assumption (the contrasts of the within-subjects design are independent) was not violated, as it is a necessary assumption for a valid F-test. Analyses indicated that this assumption was violated. However, MANOVA procedures do not require the components to be independent of one another and are used as a substitute statistic at such times (Keppel, 1982). The MANOVA test was also significant ($F(2, 34) = 5.44$, $p < .0158$), indicating a significant effect for ADMIN.

Planned comparisons for ADMIN revealed a significant difference between PRE and POST ($F(1, 17) = 9.78$, $p < .006$) as well as POST and RECOVERY ($F(1, 17) = 7.76$, $p < .013$). The means indicate there was a significant inward shift of dark vergence as a result of exposure, and a significant outward shift after the recovery period.

Paired samples t-tests reveal that dark vergence for both the Biocular and Stereoscopic conditions, but not the Vergence condition, were significantly different from the PRE-VE baseline after the 30-minute recovery period (see Table 2). An examination of the means indicates that after 30 minutes, dark vergence in these two conditions remained significantly shifted outward. No significant outward shift remained for the Vergence condition.

Planned comparisons between viewing conditions were carried out on the POST and RECOVERY values (see Sheskin, 1997). No significant differences were revealed in dark vergence after exposure to the viewing condition, or after the recovery period.

Table 2
Paired Samples t-test Comparing PRE-VE and RECOVERY Dark Vergence by View

Variable	Standard Deviation	Difference	t	P
Biocular	97.58	19.90	2.20	.042
Stereoscopic	105.87	24.13	2.61	.018
Vergence	98.60	13.34	1.91	.0720

Dark Accommodation

Table 3 presents the mean, standard deviation, and variance of dark accommodation (in diopters) values.

Table 3
Dark Accommodation Mean and Standard Deviation by View

Variable	Mean (diopters)	Standard Deviation	Variance
Pre VE	4.4694	.6939	0.4810
Pre Overall	4.4884	.7555	.571
Post Overall	4.6083	.7149	.511
Recovery Overall	4.4856	.7613	.580
Pre Biocular	4.5056	.6989	0.4880
Post Biocular	4.6056	.7696	0.5923
Recovery Biocular	4.4653	.7378	0.5443
Pre Stereoscopic	4.3583	.9600	0.9216
Post Stereoscopic	4.5625	.6723	0.4520
Recovery Stereoscopic	4.5847	.7815	0.6160
Pre-Exposure Vergence	4.6014	.7652	0.5855
Post Vergence	4.6569	.8720	0.7604
Recovery Vergence	4.4069	.9139	0.8352

A repeated measures ANOVA on the dark accommodation measure revealed only a significant effect of ADMIN ($F(2, 34) = 3.79$, $p < .033$). Again, the sphericity assumption was violated, and a MANOVA was conducted. The MANOVA revealed no significant main effect of ADMIN on dark accommodation. No planned comparisons based on the experimental hypotheses between levels of ADMIN or VIEW revealed significant differences.

Association between Dark Vergence and Dark Accommodation

To test whether or not VE represents a normal or a degraded visual environment, correlations between shifts in dark vergence and dark accommodation were performed. If the shifts are correlated (varying together), then the systems may still be normally linked indicating the environment was not degraded. On the other hand, the vergence system may shift under the degraded condition, but dark accommodation may no longer be normally coupled with it so does not shift. No significant correlations were found.

SSQ

Nausea. The mean, standard deviation, and variances for the SSQ Nausea subscale are presented in Table 4.

Table 4
Mean, Standard Deviation, and Variance of Nausea Subscale Scores by View

Variable	Mean	Standard Devation	Variance
Pre VE	2.65	5.48	30.04
Pre Overall	2.47	5.06	25.365
Post Overall	6.54	8.55	73.13
Recovery Overall	1.94	4.38	19.20
Pre Biocular	2.65	5.48	30.04
Post Biocular	7.42	10.12	102.31
Recovery Biocular	3.18	6.54	42.83
Pre Stereoscopic	2.12	6.17	38.07
Post Stereoscopic	5.83	9.89	97.85
Recovery Stereoscopic	1.59	4.91	24.09
Pre Vergence	2.65	5.48	30.04
Post Vergence	6.36	8.66	74.95
Recovery Vergence	1.06	3.09	9.52

The repeated measures ANOVA on the Nausea subscale values revealed a significant main effect only for ADMIN ($F(2, 34)$ 11.40, $p < .001$) and no interaction effect. The sphericity assumption was violated, but the MANOVA showed a significant effect for ADMIN ($F(2, 16) = 5.83$, $p < .0124$).

Planned comparisons revealed a significant difference between PRE and POST ($F(1, 17) = 10.95$, $p < .004$) and POST and RECOVERY ($F(1, 17), = 12.17$, $p < .003$). An examination of the means indicates a significant increase in Nausea subscale values as a result of VE exposure, and a significant decrease in symptoms during the intertrial recovery period. Paired samples t-tests between the RECOVERY and PRE-VE baseline value indicate no significant differences in symptoms remained after the recovery period.

Planned comparisons between viewing conditions on the POST and RECOVERY Nausea values revealed one significant difference. The RECOVERY Biocular score was significantly different from the Vergence RECOVERY score ($F(1, 17) = 4.86, p < .042$). The means indicate that after the 30-minute recovery period Nausea scores were lower for the Vergence condition than the Biocular condition. However, because all possible comparisons were made, the Bonferroni correction for multiple comparisons was warranted. This correction adjusted the critical value required to $p = .0167$. Using this criterion, this comparison was no longer significant.

Because the variance of the RECOVERY value for the Vergence condition appeared to be less than either the Biocular or Stereoscopic conditions, these variances were compared using a jack-knife test (Keppel, 1982). These analyses revealed that the Biocular condition had a significantly greater variance than the Vergence condition ($F(17, 17) = 4.50, p < .01$). The Stereoscopic condition also had a significantly larger variance than the Vergence condition ($F(17, 17) = 2.53, p < .05$). Therefore, the Vergence condition had a more consistent recovery rate for Nausea than either the Biocular or Stereoscopic conditions.

Oculomotor discomfort. The means, standard deviations, and variances for the Oculomotor Discomfort scale are presented in Table 5.

Table 5
Mean, Standard Deviation, and Variance of Oculomotor Discomfort Subscale Scores by View

Variable	Mean	Standard Deviation	Variance
Pre VE	4.21	5.94	35.30
Pre Overall	5.33	7.09	50.24
Post Overall	12.07	15.78	249.02
Recovery Overall	4.91	7.53	56.68
Pre Biocular	2.53	4.50	20.28
Post Biocular	13.48	13.65	186.26
Recovery Biocular	7.16	11.77	138.38
Pre-Stereoscopic	5.47	9.30	86.56
Post Stereoscopic	11.79	20.00	400.32
Recovery Stereoscopic	4.63	10.76	115.85
Pre Vergence	8.00	13.12	172.18
Post Vergence	10.95	18.43	339.48
Recovery Vergence	2.95	4.61	21.22

The repeated measures ANOVA revealed a significant main effect only for ADMIN ($F(2, 34)$ 8.61, $p < .001$) and no interaction effect. The sphericity assumption was violated, but the MANOVA showed a significant effect for ADMIN ($F(2, 16) = 5.27$, $p < .017$).

Planned comparisons revealed a significant difference between PRE and POST ($F(1, 17) = 8.00$, $p < .012$) and POST and RECOVERY ($F(1, 17), = 9.43$, $p < .007$) for all viewing conditions. An examination of the means indicates a significant increase in Oculomotor Discomfort as a result of VE exposure, and a significant decrease in symptoms during the recovery period. Paired samples t-tests between the RECOVERY and PRE-VE baseline value indicate no significant differences in symptoms remained after the recovery period. No planned comparisons between viewing conditions on POST or RECOVERY values revealed any significant differences.

Because the variance of the RECOVERY value for the Vergence condition appeared to be less than either the Biocular or Stereoscopic conditions, these variances were compared using a jack-knife test (Keppel, 1982). These analyses revealed that the Biocular condition had a significantly greater variance than the Vergence condition ($F(17, 17) = 6.52$, $p < .001$). The Stereoscopic condition also had a significantly larger variance than the Vergence condition ($F(17, 17) = 5.46$, $p < .001$).

<u>Disorientation.</u> The means, standard deviations, and variances for the Disorientation scale are presented in Table 6.

Table 6
Mean, Standard Deviation, and Variance of Disorientation Subscale Scores by View

Variable	Mean	Standard Deviation	Variance
Pre VE	3.09	10.19	103.85
Pre Overall	4.12	6.73	45.31
Post Overall	13.66	15.14	229.16
Recovery Overall	3.87	6.61	43.69
Pre Biocular	.77	3.28	10.76
Post Biocular	17.01	17.58	309.01
Recovery Biocular	6.96	14.52	210.86
Pre Stereoscopic	6.96	16.01	256.46
Post Stereoscopic	12.37	18.42	339.41
Recovery Stereoscopic	3.09	5.95	35.46
Pre Vergence	4.64	8.27	68.39
Post Vergence	11.60	15.29	233.66
Recovery Vergence	1.55	4.50	20.26

The repeated measures ANOVA revealed a significant main effect only for ADMIN ($F(2, 34)$ 8.99, $p < .001$) and no interaction effect. The sphericity assumption was violated, but the MANOVA showed a significant effect for ADMIN ($F(2, 16) = 4.68$, $p < .025$).

Planned comparisons on the viewing conditions revealed a significant difference between PRE and POST ($F(1, 17) = 8.68$, $p < .009$) and POST and RECOVERY ($F(1, 17)$, = 9.62, $p < .006$). An examination of the means indicates a significant increase in Disorientation as a result of VE exposure, and a significant decrease in symptoms during the recovery period. Paired samples t-tests between the RECOVERY and PRE-VE baseline value indicates no significant differences in symptoms remained after the recovery period. No planned comparisons between viewing conditions on POST or RECOVERY values revealed any significant differences.

Because the variances of the RECOVERY value for the Vergence and Stereoscopic conditions appeared to be less than the Biocular condition, these variances were compared using a jack-knife test (Keppel, 1982). These analyses revealed that the Biocular condition had a significantly greater variance than the Vergence condition ($F(17, 17) = 10.41$, $p < .001$). The Biocular condition also had a significantly larger variance than the Stereoscopic condition ($F(17, 17) = 5.95$, $p < .001$).

Total severity. The means, standard deviations, and variances for the Total Severity scale are presented in Table 7.

Table 7
Mean, Standard Deviation, and Variance of Total Severity Subscale Scores by View

Variable	Mean	Standard Deviation	Variance
Pre VE	3.95	5.66	32.04
Pre Overall	4.71	6.04	36.49
Post Overall	12.19	14.67	215.13
Recovery Overall	4.22	6.21	38.61
Pre Biocular	2.49	4.06	16.46
Post Biocular	14.13	14.37	206.61
Recovery Biocular	6.65	10.62	112.82
Pre Stereoscopic	5.40	10.12	102.39
Post Stereoscopic	11.43	18.34	336.48
Recovery Stereoscopic	3.74	8.01	64.18
Pre Vergence	6.23	9.34	87.22
Post Vergence	11.01	15.53	241.03
Recovery Vergence	2.29	3.43	11.75

The repeated measures ANOVA revealed a significant main effect only for ADMIN ($F(2, 34)$ 10.81, $p < .001$) and no interaction effect. The sphericity assumption was violated, but the MANOVA showed a significant effect for ADMIN ($F(2, 16) = 6.31$, $p < .010$).

Planned comparisons on the viewing conditions revealed a significant difference between PRE and POST ($F(1, 17) = 10.18$, $p < .005$) and POST and RECOVERY ($F(1, 17)$, $= 11.61$, $p < .003$). An examination of the means indicate a significant increase in Total Severity as a result of VE exposure, and a significant decrease in symptoms during the recovery period. Paired samples t-tests between the RECOVERY and PRE-VE baseline value indicate no significant differences in symptoms remained after the recovery period. No planned comparisons between viewing conditions on POST or RECOVERY values revealed any significant differences.

Because the variance of the RECOVERY value for the Vergence condition appeared to be less than either the Biocular or Stereoscopic conditions, these variances were compared using a jack-knife test (Keppel, 1982). These analyses revealed that the Biocular condition had a significantly greater variance than the Vergence condition ($F(17, 17) = 9.60$, $p < .001$). The Stereoscopic condition also had a significantly larger variance than the Vergence condition ($F(17, 17) = 5.46$, $p < .001$).

Comparison between subscales. For each condition, the rank order of the SSQ subscales indicated that immediately after exposure Disorientation symptoms were greatest followed by Oculomotor Discomfort with Nausea being the least severe symptom. However, after the 30-minute recovery period although Nausea remained the lowest, Oculomotor Discomfort was the greatest with Disorientation lying in between these two.

In addition, for the Biocular and Stereoscopic conditions, there was a significant difference between the POST subscale values $F(2, 34) = 8.21$, $p < .001$ and $F(2, 34) = 5.18$, $p < .011$, respectively. Post-hoc comparisons indicate that in both conditions, Nausea was significantly less than both Disorientation (Biocular: $p < .001$; Stereoscopic: $p < .017$) and Oculomotor Discomfort (Biocular: $p < .042$; Stereoscopic: $p < .032$).

SSQ subscale associations with other measures. It was hypothesized that there would be a correlation between shifts in dark vergence and changes in SSQ subscale scores. Significant correlations between these measures indicate that as dark vergence shifted inward (decreased), there was an increase in SSQ symptoms (see Table 8).

Table 8
Correlations of SSQ Subscale Scores with Dark Vergence

SSQ Subscale	Correlation	p
Nausea	-.330	.001
Oculomotor Discomfort	-.360	.001
Disorientation	-.253	.001
Total	-.343	.001

No significant correlations between shifts in dark accommodation and SSQ scores were found.

Post-hoc Analyses

A difference between viewing conditions was expected, but none was found. However, there is some indication from one Planned Comparison that a difference in Nausea between the Biocular and Vergence conditions existed, but that conclusion was rendered questionable after applying the Bonferroni correction for multiple comparisons. In addition, there was significantly less variance in RECOVERY values for the Vergence compared to Biocular condition for all SSQ measures, and less variance for the Vergence condition than the Stereoscopic condition for those measures, except for Disorientation. Based on the literature review indications and the non-significant results for a possible difference between the viewing conditions mentioned above, exploratory Tukey post-hoc analyses on the interactions were carried out. A number of significant differences were revealed. Table 9 presents these statistics. (Note: a negative value for dark vergence indicates an inward shift and a negative value for SSQ subscales indicates a lessening of symptoms.)

Distance Estimation

Distance estimations were divided into 5-foot groupings. The average distance estimations are presented in Table 10. For each of these 5-ft groupings, a single-factor repeated measures ANOVA was performed on the distance estimations for each viewing condition in relation to the actual distance of the block. As Table 11 indicates, estimations at every distance were significantly different from the actual distance. An examination of the means in Table 10 shows that distance estimations in the VE were significantly lower than the actual distances.

Repeated measures ANOVA revealed no significant difference for distance estimation by view.

The literature indicated there might be a relationship between distance estimation and dark vergence. An inspection of the data revealed that, although participants were not accurate in their distance estimations, they did appear to have a relatively consistent error in their estimations. Specifically, their distance estimations could be described by a simple

Table 9
Post-hoc Analyses by View and Variable

Condition	Variable	Comparison	Mean Difference	p
Biocular				
	Dark Vergence			
		Pre-Post	-44.95	.001
		Post-Recovery	36.9	.004
	Nausea			
		Pre-Post	4.77	.016
		Post-Recovery	-4.24	.049
	Oculomotor Discomfort			
		Pre-Post	10.95	.033
	Disorientation			
		Pre-Post	16.24	.001
	Total Severity			
		Pre-Post	11.64	.001
Stereoscopic				
	Dark Vergence			
		Pre-Post	-42.12	.001
		Post-Recovery	32.31	.023
	Nausea			
		Post-Recovery	-4.24	.049
	Total Severity			
		Post-Recovery	-6.03	.041
Vergence				
	Dark Vergence			
		Pre-Post	-42.33	.001
		Post-Recovery	41.20	.001
	Nausea			
		Post-Recovery	-5.30	.047
	Total Severity			
		Post-Recovery	-8.73	.011

linear relationship, that of a slope of a line. Therefore, an average slope for each individual's distance estimation was calculated for each viewing condition. This slope was derived by

Table 10
Mean Distance Estimations in 5-foot Groupings by View

Range (in feet)	Biocular	Stereoscopic	Vergence
1-5	1.23	1.25	1.20
6-10	3.42	3.15	3.41
11-15	6.47	6.06	6.54
16-20	9.74	9.74	9.74
21-25	13.16	13.01	13.31
26-30	16.53	16.39	17.19

Table 11
Comparison of Distance Estimations with Actual Distance for each View

Range	Condition	Mean Square	Df	F	p
1-5	Biocular	56.13	1	109.64	.001
	Stereoscopic	54.80	1	176.84	.001
	Vergence	58.08	1	162.95	.001
6-10	Biocular	338.00	1	88.10	.001
	Stereoscopic	381.57	1	203.01	.001
	Vergence	339.45	1	105.52	.001
11-15	Biocular	826.61	1	71.37	.001
	Stereoscopic	930.18	1	124.40	.001
	Vergence	811.15	1	57.18	.001
16-20	Biocular	1229.53	1	42.11	.001
	Stereoscopic	1485.13	1	91.69	.001
	Vergence	1226.78	1	48.26	.001
21-25	Biocular	1743.53	1	35.55	.001
	Stereoscopic	1797.33	1	35.86	.001
	Vergence	1689.42	1	35.78	.001
26-30	Biocular	2369.40	1	26.58	.001
	Stereoscopic	2426.33	1	31.37	.001
	Vergence	2131.32	1	23.50	.001

arranging distance estimations in ascending order based upon the actual distance to the object. Delta x was the difference in estimation between "successive" estimations when arranged in ascending order. Delta y was then the difference in actual distance between

successive estimation. This slope was then correlated with the measures of dark vergence. All correlations were significant (see Table 12).

Table 12
Correlations between Dark Vergence and Slope of Distance Estimation

Slope	DV Measure	Correlation	p
Biocular	Pre	.664	.003
	Post	.756	.001
Stereoscopic	Pre	.592	.010
	Post	.666	.003
Vergence	Pre	.541	.021
	Post	.659	.003

In every instance the greater the slope, the greater the dark vergence measure. Given that distance estimations were low, the higher slope indicates more accurate distance estimation. Therefore, the greater the dark vergence, the more accurate the distance estimation. No significant correlations between the magnitude of the dark vergence shift and magnitude of the distance estimation error were found.

Discussion

Simulator Sickness

Overall, the expected patterns of simulator sickness symptoms were found for dark vergence. Given that the pre-VE dark vergence baseline for all participants was greater than the convergence point of the HMD, there was a significant inward shift in dark vergence as a result of VE exposure. This indicates stress upon the vergence system that is attempting to fixate on objects (the screens) at a close distance. After a recovery period, dark vergence shifted outward as the oculomotor system was no longer under the strain of having to fixate on near objects and was therefore able to readjust outwards towards its pre-VE baseline. Despite this general trend of an outward shift during the recovery, for both the Biocular and Stereoscopic conditions, dark vergence remained significantly inward of the pre-VE baseline after the recovery period. This pattern was somewhat unexpected as it was hypothesized that after 30 minutes all symptoms would return to baseline. However, that people appeared to recover more fully from the Vergence condition was not surprising, as it was believed to be the least stressful condition. The lack of lingering symptomatology compared to the other conditions supports this hypothesis.

Dark accommodation did not significantly change for any condition over any administration. Research shows that the accommodative system is harder to fatigue than the vergence system (Lie & Watten, 1991). The exposure in this experiment may not have been long enough to fatigue accommodation and therefore induce in a shift in dark accommodation.

The lack of correlation between shifts in dark vergence and dark accommodation was expected. Normally these processes are synergistically linked together so a change in one produces a corresponding change in the other. However, under reduced cue conditions they do not interact predictably. It was hypothesized that VE is a reduced cue environment and therefore dark accommodation and dark vergence would act independently, i.e., would not be correlated. The lack of a significant correlation may indicate that they were indeed acting independently. However, it may not be that the VE is a sufficiently reduced cue environment as to cause the link between these processes to weaken. Rather, the exposure may not have been long enough to sufficiently fatigue the accommodative system and produce shifts in dark accommodation. Although the latter hypothesis reflects a disjunct between vergence and accommodation, it is not based on the degraded visual condition, but on the slower fatigability of the accommodative system during near work. A similar argument cautions that improvements in HMD technology may have eased the onset of fatigue. Finally, the methods used in this study to measure dark accommodation and dark vergence may not have been sensitive or accurate enough to find a relationship between the two processes.

The increase in SSQ symptoms as a result of VE exposure was expected, as was the significant improvement in symptoms during the intertrial recovery period. As hypothesized, after the recovery period these symptoms were not significantly different from the pre-VE baseline. The significant correlation between shifts in dark vergence and these changes in SSQ symptoms suggests that dark vergence may be a supplemental objective measure of duress due to VE exposure. As dark vergence shifts inward, there is an increase in subjective symptoms; as it shifts outward, there is a decrease in symptoms.

Despite the confirmation of the generally predicted patterns in symptomatology, the lack of strong significant effects for viewing condition is surprising, as are the indications of a disadvantage for the Biocular condition compared to the other conditions. It was anticipated that the Stereoscopic condition would be the most stressful. This prediction was based on not only the physiological processing of stereoscopic information, but also previous research with HMDs. Because the perspective in the standard Stereoscopic condition does not contain the "rotational" information that was supplied in the Vergence condition, it was believed that this mismatch would create more problems for the visual system. The visual system would not receive proper visual information, which would create visual strain. The lack of a main effect for view indicates there may be no such confusion or difficulty on the part of the processing system.

Further, several research studies have found an advantage for Biocular over Stereoscopic viewing. In a direct comparison of viewing conditions with the same HMD over a variety of tasks, Singer, Ehrlich, Cinq-Mars, and Papin (1995) found that a Stereoscopic view resulted in greater Nausea than a Biocular view. However, this study used an older-generation HMD. Because there was no mechanical adjustment to bring the two views together, Fresnel lenses were placed over the screens to bring the two views together. This procedure may have acted, in effect, like a partial static Vergence condition. Although the perspectives the eyes received did not change because of the Fresnel lenses,

the eyes may have been forced to converge to a different point than the physical screens, which might have been more important in reducing sickness than the graphical representation. In another study indicating preference for Biocular over Stereoscopic HMDs, Rushton et al.(1994) compared two different generations of HMDs. Their results may have been due to other changes in HMD technology, computer hardware or software technology, between the studies rather than the different viewing conditions, though this cannot be proven by their study.

Because this study directly compared the different viewing conditions using the same HMD, hardware, software, and stimuli in a within subjects design to reduce inter-subject variability, the results of this study suggests more firmly there may not be an advantage for Biocular over Stereoscopic viewing. On the contrary, there may be a disadvantage for the Biocular compared to the Stereoscopic view. Post-hoc analyses suggest that Nausea, Oculomotor Discomfort, Disorientation and Total Severity may be greater in the Biocular compared to the Stereoscopic condition. These findings are merely suggestive; not conclusive as they were post-hoc analyses conducted on a non-significant interaction. Further study is needed to determine the relationships between simulator sickness and viewing conditions suggested by these ancillary analyses.

Another unanticipated finding involves the variability in the SSQ subscales after the 30-minute recovery period. For all subscales, the variance in the Vergence condition was the least. Because the means were not significantly different between the viewing conditions, this reveals a more consistent, predictable recovery from Vergence viewing. On the other hand, recovery values in the Biocular condition were the most variable, suggesting it is more difficult to predict how well someone will recover from exposure to that condition. The greater variance indicates that in the Biocular condition there were people who recovered both more fully than they did from the Vergence condition and others who recovered much less than they did from the Vergence condition. Because eliminating extremely poor recovery from an exposure is desirable, these results favor using the Vergence condition. The lower recovery variance in the Stereoscopic condition compared to the Biocular condition for Disorientation similarly suggests an advantage for Stereoscopic over Biocular viewing. However, because the greater variance also means that some recovered more fully from exposure to the Biocular and Stereoscopic conditions, it would be beneficial to be able to predict beforehand which condition is best for a particular individual. A predictor test would allow greater customization for VE users. It would also help reduce lingering effects of VE exposure and even dropout rates with repeated exposures as individuals are better able to recover during rest periods. Unfortunately the results of this study do not shed any light on what measures might be used in a predictive test.

Distance Estimation

It was predicted that the Vergence condition would lead to more accurate distance estimation than either the Stereoscopic or Biocular views. This hypothesis was not supported. No viewing condition was significantly different from any other viewing condition. Overall, people were very poor at distance estimation. Analyses indicated that for each viewing condition and at each distance, people significantly underestimated the

distance to objects in the VE. It is possible that the optics of the HMD (e.g., the focal length of the lens system) were responsible for the misperceptions in depth.

However, analyses revealed an inward shift in dark vergence as a result of VE viewing, indicating the vergence system was straining to fixate on an object closer than the participants' set point for vergence. As noted earlier, normal distance perception is a function of the deviation from the resting state vergence. For example, the effort required to fixate a target which is closer than the individual's set point results in the perception that the object is close, rather than far away (Owens, 1987). How close such an object is judged to be is a function of how much convergence effort is required. The inward shift in the dark vergence point during VE viewing may indicate that participants needed to converge the eyes even if objects were located further away in the virtual world than the vergence set point. As a result of this continued convergence (near fixation) effort no matter the distance, there may have been an overall reduction in the perception of distance.

For each viewing condition, there was a strong significant positive correlation between the dark vergence value and distance estimation. The greater the dark vergence value, the higher the distance estimations. Because distance was generally underestimated, the greater distance estimation indicates more accurate distance estimation for greater dark vergence values. There were no significant correlations between distance estimation and dark accommodation or SSQ subscale measures. Therefore, as indicated by the literature, of the variables investigated in this study, dark vergence is the only factor associated with distance estimation. The greater an individual's set point for dark vergence, the more accurate their distance estimations were in the VE. This finding indicates there is an individual physiological difference affecting distance estimation accuracy in a VE. It is not clear from the present study whether environmental cues, such as occlusion or size differences, might be more prominent distance cues in a more complex environment.

This result appears to contradict the above argument that the greater the shift in dark vergence, the greater the inaccuracy (underestimation) of distance. However, the magnitude of the dark vergence shift did not correlate with the magnitude of the misestimations as predicted. This may be an artifact of the experimental method. The primary focus of this study was the objective (dark vergence) and subjective (SSQ) responses to the different viewing conditions. To investigate these issues it was important that the individual look at objects at varying distances and while moving towards objects at varying distances. Because the tasks needed to have real world validity (e.g., rooms normally have objects at varying distances and people move to objects at various distances), in designing the experiment, these concerns had to take precedence. One problem with the repeated measures design is that despite counterbalancing, after the first exposure people likely developed a metric of sizes and distances. For ensuing trials, they experienced the same rooms in a different order. It is not likely that participants suddenly decided the metric of the room had changed. Alternatively, it may be that contrary to studies conducted in the real world on dark vergence and distance estimation that vergence has no effect on distance estimation in a VE. Although every attempt was made to reduce the effect of other cues to distance such as occlusion and perspective, these cues may still have had greater effect on distance estimation than oculomotor feedback from the vergence effort.

Therefore, unfortunately, the tasks were not optimal to investigate the effect of dark vergence shifts on distance estimation in general, let alone at specific ranges of distances and under the various viewing conditions. The only reliable conclusion that can be drawn is that in general there is a significant positive correlation between distance estimations and dark vergence. The greater the dark vergence, the more accurate are the distance estimations. Owens and Leibowitz (1976) found a similar correlation between dark vergence and distance estimation accuracy in the real world. Other than this finding, this study provides additional support for previous studies indicating that people significantly underestimate distances in VE (Singer et al., 1995; Witmer & Sadowski, 1998).

General Conclusions

These findings suggest that most participants might experience less simulator sickness with a Vergence viewing condition. This conclusion is based on two separate results. First, the paired t-tests indicated that only after the Vergence condition did dark vergence return to its pre-VE exposure level after the 30-minute recovery period. Second, there was less variance in recovery ability from the Vergence condition during this time, compared to the Biocular and Stereoscopic conditions on most measures. A main effect for administration time indicated that for all measures except dark accommodation there was a significant increase in symptomology as a result of VE exposure, and a significant decrease in symptoms during the 30-minute intertrial recovery period. However, there was no main effect for viewing condition across the measures. Because differences between viewing conditions were expected, and one planned comparison for Nausea between the Biocular and Vergence condition weakly suggested greater recovery ability in the Vergence condition, post-hoc comparisons were carried out. These comparisons indicate that the Biocular condition was the most symptomatic condition, producing increased symptoms on all subjective SSQ measures of discomfort. Post-hoc comparisons also revealed that both the Stereoscopic and Vergence conditions resulted in significant recovery from any Nausea and Total Severity increases due to VE exposure. Therefore, the following conclusions can be marginally supported, in addition to the prior tentative deduction: the Biocular condition is the most stressful condition, with the Stereoscopic condition producing effects that fall between those of the Biocular and Vergence conditions.

This study also shows a wide range of individual differences in symptomatic recovery from VE exposure. As such, Vergence viewing should not be expected to eliminate dropouts, but could be expected to reduce the number of dropouts when repeated exposures are involved. The Vergence condition appears to be the "safest" condition. In other words, the lower variance in recovery measures in the Vergence condition suggests that overall people recover most consistently from this condition. Although some people recover better in either the Biocular or the Stereoscopic condition, others experience much more difficulty recovering from these conditions compared to the Vergence condition. Since no predictive measures currently exist to determine beforehand which condition will be best for a given individual, by eliminating the poor recovery extreme, the Vergence condition may be the safest condition to use, although it is not necessarily optimal for everyone.

Finally, it may be prudent to use multiple measures of symptomology not only to help identify individuals who are under duress, but to better assess when they have achieved readaptation. One candidate measure is dark vergence, given its objective scaling, its relevance to readaptation, and its correlation with SSQ subscale scores.

Future Research

Although it was suggested in the preceding discussion that the Vergence condition is the best condition and the Biocular likely the worst, these are not obvious or clear-cut conclusions. Although the comparison of the recovery dark vergence to the pre-VE exposure baseline indicates an advantage for the Vergence condition, the remainder of the recommendations are based primarily on the value of eliminating variance in recovery and post-hoc analyses of a non-significant interaction. As noted above, it is clear there are large individual differences. Therefore, one of the strongest recommendations from this study for future research concerns finding a set of predictor variables that can determine, prior to VE exposure, what condition would best suit a given individual. A small battery of tests or measurements that could hold such predictive power might not only reduce discomfort of users of VE, but might also help reduce the levels of simulator sickness. Unfortunately, the current study does not shed any light on what measures to include. None of the pre-exposure measures correlated with symptomology within or across conditions and the literature reviewed does not offer any clues.

Another avenue for future investigation is the effect of repeated exposures to the VE for various viewing conditions. Because a reduction in SSQ recovery variances was found in the Vergence condition, across numerous users Vergence presentation should reduce the severity of symptoms from repeated exposure to VEs. However, this hypothesis is based on the outcome of one exposure to that condition intertwined with exposures to the other conditions. The question remains as to whether or not the Vergence condition would really reduce the number of withdrawls from the system, or severity of symptoms after repeated exposure. It is further anticipated that the disadvantages weakly suggested in the post-hoc analyses for the Biocular condition would become more prominent with repeated exposures. By being exposed to the same condition repeatedly, individuals might be less able to recover than if they were exposed to different conditions that are easier on their physiological systems. With a reduced recovery opportunity, effects could accumulate and become more prominent over time and with repeated exposures to the more stressful condition.

Repeating this study using more complex and realistic environments would be useful. In order to reduce the effect of extraneous variables on symptoms, a simple environment was used. This study should be repeated using a more complex, object-dense environment as well as a more complex task or set of tasks to assess the effects in a more realistic environment. The advantage for the Vergence condition may become stronger in such environments and with different tasks due to increased fixating demands on multiple targets at different depths. Similarly, such research may also show whether or not the Biocular condition does result in greater symptoms or, as the primary analyses in this study show, it is essentially no different than the Stereoscopic condition.

The value of adding an eye-tracker to the Vergence condition needs close consideration. This study did not use an eye-tracker to determine where the individual was actually looking. Instead the system determined what was in the center of the field of view and based the rotational value of the Vergence graphics on that object. Although the experimenter instructed the participant to keep his or her eyes open at all times and center objects in the field of view, in addition to watching a monitor to make sure he or she was doing the latter, it was an imperfect system. The HMD could slip on the head so the participant was not actually looking at the center of the screens, though the view presented on the monitor indicated the participant was looking at the center of the screens. Even if the HMD was centered properly and the participant instructed to look only at the center of the screens, he or she could have been looking around inside the HMD rather than centering objects. As a result, the Vergence calculations may not have been accurate, and could even be erroneous enough to induce symptoms. An eye-tracking system and vergence calculations based on the gaze position of the eye-trackers may provide more benefit.

In terms of dark vergence, two important questions were not addressed in this study. Given that there was an inward shift in dark vergence as a result of viewing a VE, what real world task produces a similar inward shift? Studies indicate there are inward shifts after reading a book or viewing a computer screen, and that the greater the shift the greater the oculomotor discomfort from that shift. This study does not indicate if viewing a VE is more like viewing a computer screen, reading a book, or some other activity. In addition, it does not answer what the equivalent viewing distance from this other task would be. Is VE like reading a book or viewing a computer screen equivalently far away as HMD screens, or as if these other objects were some other distance away? What would that distance be?

As for distance estimation, there should be more concentrated research on the effect of viewing condition on distance estimation. One problem with the repeated measures design and the type of counterbalancing used is that it is very possible that after the first exposure, participants develop a metric of sizes and distances. For ensuing trials, they were aware they received the same rooms merely in a different order. In that case, it is unlikely they suddenly decided the metric of the room had changed. Therefore, the cognitive model and decisions about the size of the room and distances to the objects may have determined the perceived distance to objects in whatever condition followed the first trial. Because distance estimation was a secondary task, and the focus of the study was the objective and subjective responses to the VE, the stimulus across conditions had to remain constant. Therefore, studies examining the potentially different geometries of space associated with the three viewing conditions would be beneficial, as this concept may not have been adequately tested in this study. Such research should utilize either a between subjects design or a larger sample completely counterbalancing varying stimuli across viewing conditions. Similarly, the effect of dark vergence shifts on distance estimation should be the focus of research. Due to the nature of the primary tasks in this study, it was not well suited to investigate the relationship between dark vergence shifts and estimations to specific distances. Only an overall comparison of dark vergence and distance estimation accuracy was possible. A more concentrated study on the effect of dark vergence set points and dark vergence shifts on distance estimation is advisable.

References

Best, P. S., Littleton, M. H., Gramopadhye, A. K. & Tyrrell, R. A. (1996). Relations between individual differences in oculomotor resting states and visual inspection performance. Ergonomics, 39(1), 35-40.

Ehrlich, J. A. (1997). Simulator sickness and hmd configurations. In M. Stein (Ed), SPIE Proceedings: Vol. 3206. Proceedings of the SPIE telemanipulation and telepresence technologies IV, (pp. 170-178). Bellingham, WA: SPIE.

Ehrlich, J. A. & Kolasinski, E. M. (1998). A comparison of sickness symptoms between dropout and finishing participants in virtual environment studies. Proceedings of the human factors and ergonomics society 42nd annual meeting, (pp. 1466-1470). Santa Monica: Human Factors and Ergonomics Society.

Enright, J. T. (1987a). Perspective vergence: Oculomotor responses to line drawings. Vision Research, 27, 1513-1526.

Enright, J. T. (1987b). Art and the oculomotor system: Perspective illustrations evoke vergence changes. Perception, 16, 731-746.

Fischer, R. E., Reiley, D. J., Pope, C., & Peli, E. (in press). Methods for improving depth perception in HMDs. In J.A. Ehrlich & S.L. Goldberg (Eds.), The capability of virtual reality to meet military requirements. NATO Technical Report.

Gallahue, D. L. (1982). Effect of movement and vision on visual-motor adjustment to optical rearrangement. Perceptual and Motor Skills, 54(3, Pt 1), 935-942.

Heuer, H. H. & Owens, D. A. (1989). Vertical gaze direction and the resting point of the eyes. Perception, 18(3), 363-377.

Hettinger, L. J., Berbaum, K. S., Kennedy, R. S., Dunlap, W. P., & Nolan, M. D. (1990). Vection and simulator sickness. Military Psychology, 2(3), 171-181.

Jachinski-Kruza, W. (1991). Eyestrain in vdu users: Viewing distance and the resting position of ocular muscles. Human Factors, 33(1), 69-83.

Kandel, E. R., Schwartz, J. H., & Jessell, T. M. (1991). Principles of neural science. Norwalk, Connecticut: Appleton & Lange.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). A simulator sickness questionnaire (SSQ): A new method for quantifying simulator sickness. International Journal of Aviation Psychology, 3(3), 203-220.

Keppel, G. (1982). Design and analysis: A researcher's handbook. Englewood Cliffs, NJ: Prentice-Hall.

Kolasinski, E. M. (1995). Simulator sickness in virtual environments. (Technical Report 1027, ADA 295 861), U.S. Army Research Institute for the Behavioral & Social Sciences, Alexandria, VA.

Kolasinski, E. M. (1996). Prediction of simulator sickness in a virtual environment. Dissertation Abstracts International, 57, 3B. (University Microfilms No. AAI9621485)

Leibowitz, H. W. & Owens, D. A. (1975a). Night myopia and dark focus of accommodation. Journal of the Optical Society of America, 65, 1121-1128.

Leibowitz, H.W. & Owens, D. A. (1975b). Anomalous myopias and the intermediate dark focus of accommodation. Science 189, 646-648.

Lie, I. & Watten, R.G. (1991). VDT work, oculomotor strain, and subjective complaints: An experimental and clinical study. Ergonomics, 37(8), 1419-1434.

Miller, M. J. (1990). Pitfalls in the conception, manipulation, and measurement of visual accommodation. Human Factors, 32(1), 27-44.

Miller, R. J., Pigion, R. G., Wesner, M. F., & Patterson, J. G. (1983). Accommodation fatigue and dark focus: The effects of accommodation-free visual work as assessed by two psychophysical methods. Perception and Psychophysics, 34(6), 532-540.

Mon-Williams, M., Wann, J. P., & Rushton, S. (1993). Binocular vision in a virtual work: Visual deficits following the wearing of a head-mounted display. Opthalmic and Physiological Optics, 13, 387-391.

Mon-Williams, M., Wann, J. P., & Rushton, S. (1995). Design factors in stereoscopic virtual-reality displays. Journal of the SID, 3(4), 207-210.

National Research Council (1997). Tactical display for soldiers: Human factors considerations. Washington, D. C.: National Academy Press.

Ostberg, O. (1980). Accommodation and visual fatigue in display work. In E. Grandjean & E. Vigliani (Eds.), Ergonomic aspects of visual display terminals (pp. 41-52). London: Taylor & Francis.

Owens, D. A. (1984). The resting state of the eyes. American Scientist, 72(4) 378-387.

Owens, D. A. (1987) Oculomotor information and perception of three-dimensional space. In H. Heuer & A. F. Sanders (Eds), Perspectives on perception and action (pp. 214-248). Hillsdale, NJ: Lawrence Erlbaum.